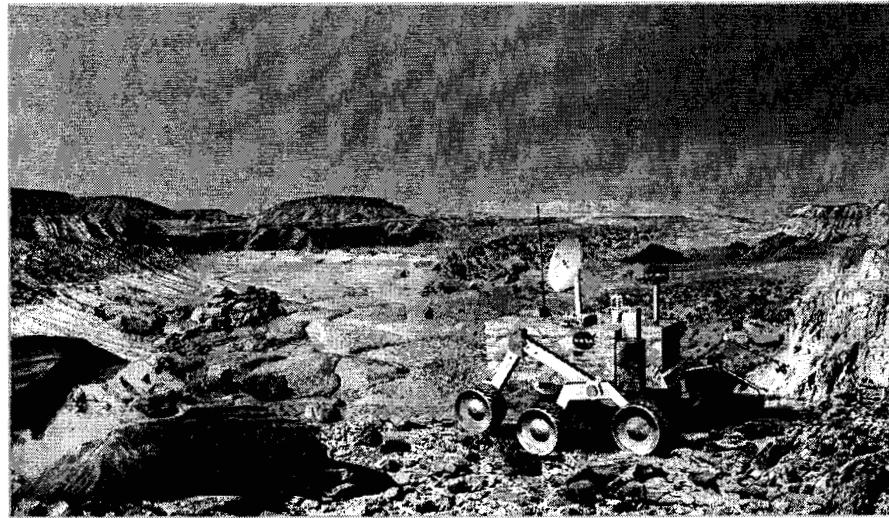# Continuous Planning
for an Autonomous Rover

Tara Estlin, Forest Fisher, Daniel Gaines,
Caroline Chouinard, Steve Schaffer, and Issa Nesnas

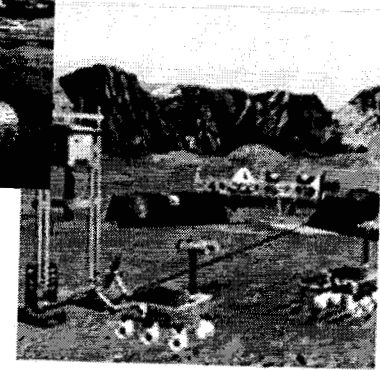NASA Jet Propulsion Laboratory
California Institute of Technology

Unmanned Vehicle Office Presentation

Why Autonomous Rovers?

- A number of upcoming missions involve robotic explorers
- Rovers require capabilities for:
  - Long-range traverses
  - Numerous science experiments
  - Opportunistic science
  - Failure recovery
- Key aspect of rover missions is the generation and execution of command sequences

  Sojourner and `03 Mars Exploration Rovers (MER) mission model is to generate sequences on ground
  - Significant manual effort
  - Rovers have limited ability to react if something unexpected happens during sequence execution
    - E.g., navigation problem, out-of-range sensor reading, new science op
  - Typical procedure is to safe rover and wait for ground communication – causes hours of lost science time!

- Planning system is part of rover's onboard software
  - Intended to run with minimal communication w/ ground
  - Interacts directly with low-level rover control software
- Operation overview:
  - Accepts science and engineering goals
  - Has model of rover operations, resources, and flight rules (e.g., power constraints, action A must precede action B, etc.,)
  - Creates a rover command sequence (or plan) to achieve as many goals as possible
  - Executes plan on low-level control software
  - Receives updates on state and resource data (e.g., energy, memory position)
  - *Continually* monitors execution and re-plans when problems, new goals or unexpected events are detected
- Have tested with several different hardware platforms, including Rocky 7, Rocky 8, and FIDO
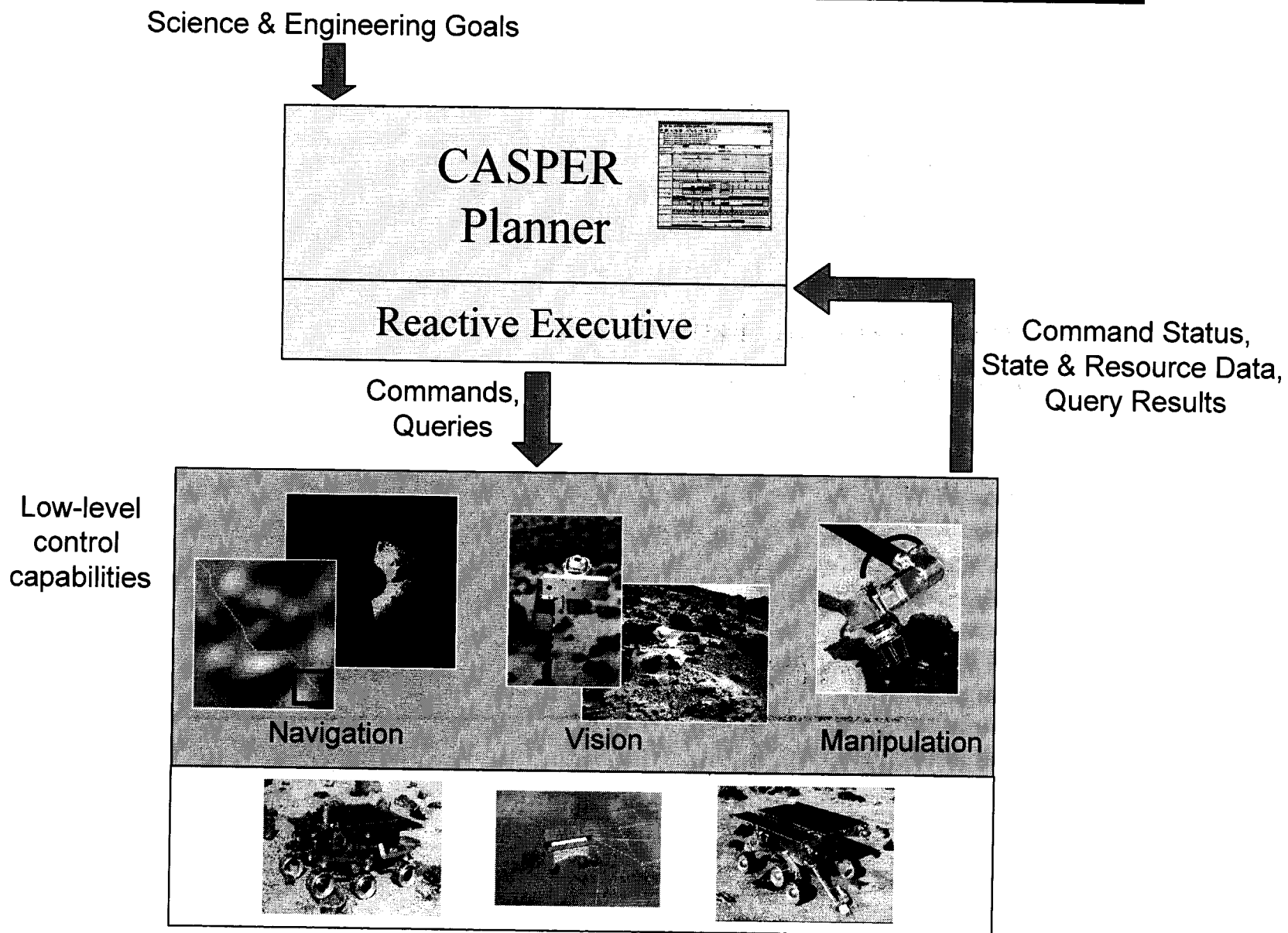
Challenges

- Onboard system needs to reason about a rich model of resource and temporal constraints
  - Must be capable of generating valid command sequences
  - Should be capable of making science/resource trade-offs
- Must perform and/or interact with spatial-reasoning and navigation capabilities
  - Dominating characteristic of rover ops is traversing to waypoints
  - Planning and exec s/w must coordinate with several levels of navigation software
    - Path planning, obstacle avoidance, position estimation, etc.
- Must handle high degree of uncertainty since exploring unknown terrain
  - Power/memory estimations
  - Duration/temporal estimations
  - Position estimation
  - Action success

System Overview

Science & Engineering Goals

CASPER Planner

Reactive Executive

Commands,
Queries

Command Status,
State & Resource Data,
Query Results

Low-level
control
capabilities

Navigation   Vision   Manipulation

CASPER Continuous Planner

- Uses model of rover activities to construct or modify a plan
  - *Example goals:* science requests, downlink requests
  - *Example actions:* move to new location, unstow mast, image, spectrometer read, transmit data
  - *Example constraints:* memory, power, time, position, sun angle
- Performs initial plan generation and continuous modification of rover plan
  - Monitors state and resource updates
  - Accepts new goal information
  - Uses iterative repair algorithm to repair plan inconsistencies
  - During plan modification, activities could be added, reordered, deleted, etc.
  - Plan rarely has chance to get significantly out of sync
- Enables system to achieve high-level of responsiveness
- Initial plan can be automatically or hand-generated

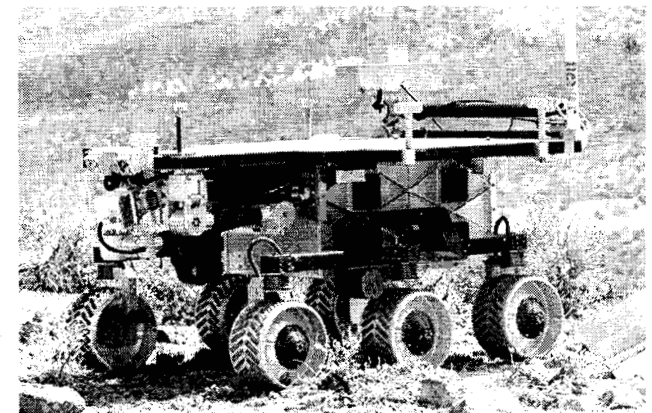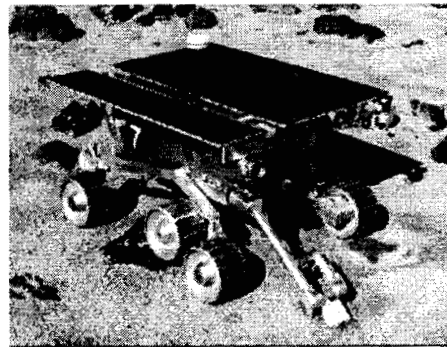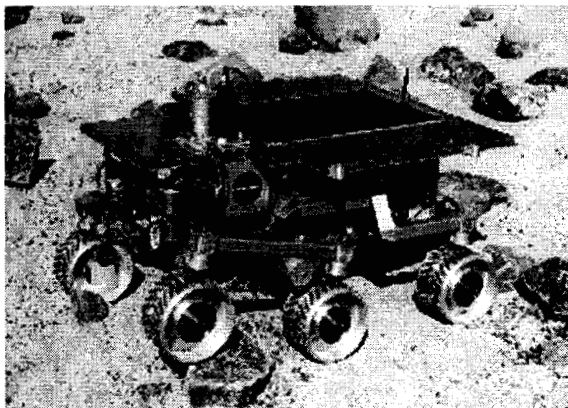# *CASPER Interface*

Activities

Resources

States

Time
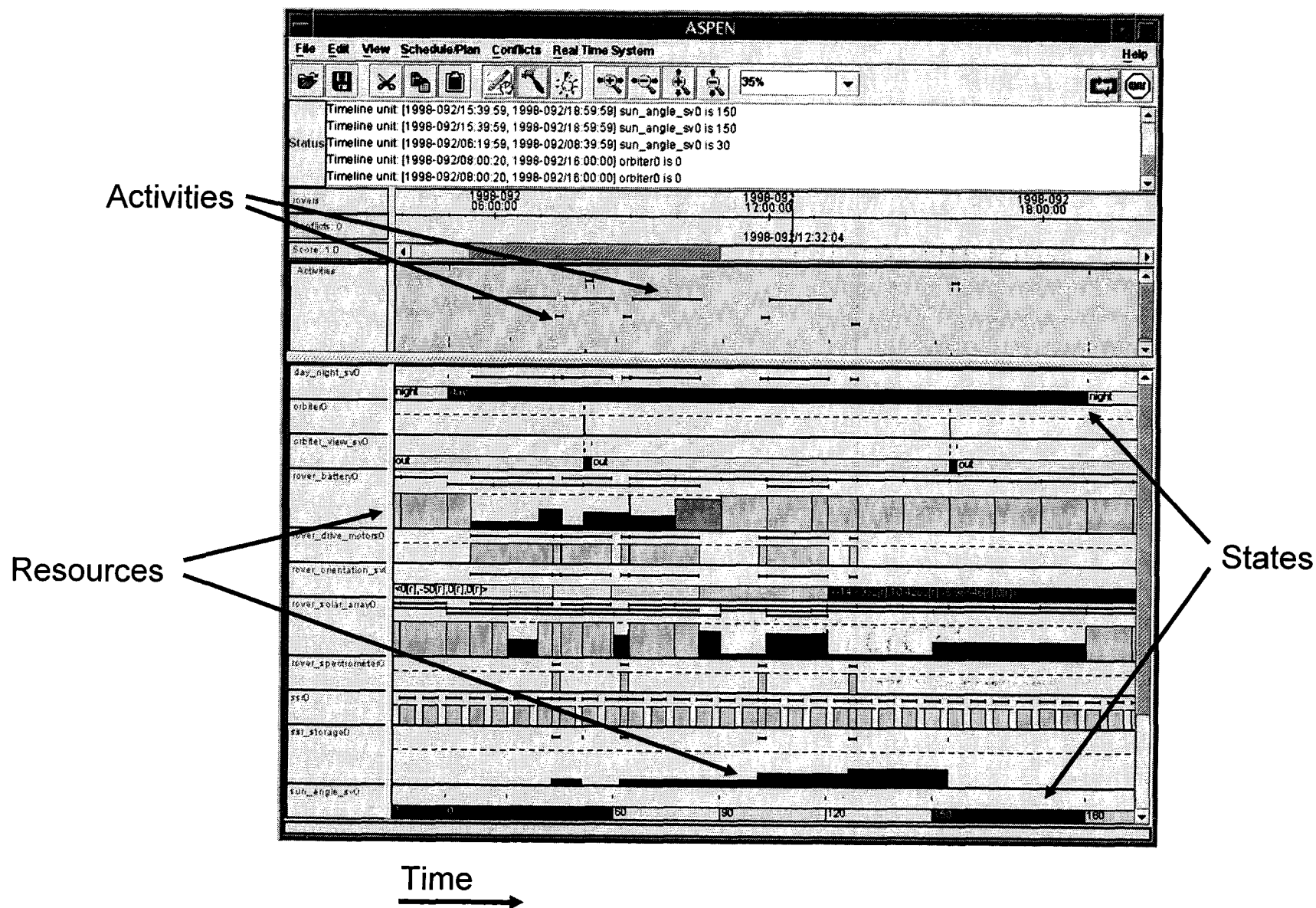
Rover Testing

- System has been tested on several different rovers and in simulation
  - Rocky 7, Rocky 8, and FIDO rover prototypes
 - ROAMS rover simulation tool

Testing Scenario Description

- Multiple science targets and obstacles identified on map
  - More science goals than can be achieved based on resource levels
  - Science goals are given priority levels
- Initial plan generation selects set of targets and waypoints
  - Uses TSP algorithm to minimize traverse distance when ordering targets
- During plan execution, system monitors command status and states/resources (i.e., position, power, memory)
- Dynamic plan modifications:
  - Obstruction in planned path causes activity re-ordering
  - Memory over-subscription – science activity uses extra memory
  - Energy over-subscription – science activity uses extra energy

Known Obstacle
Planned Activity
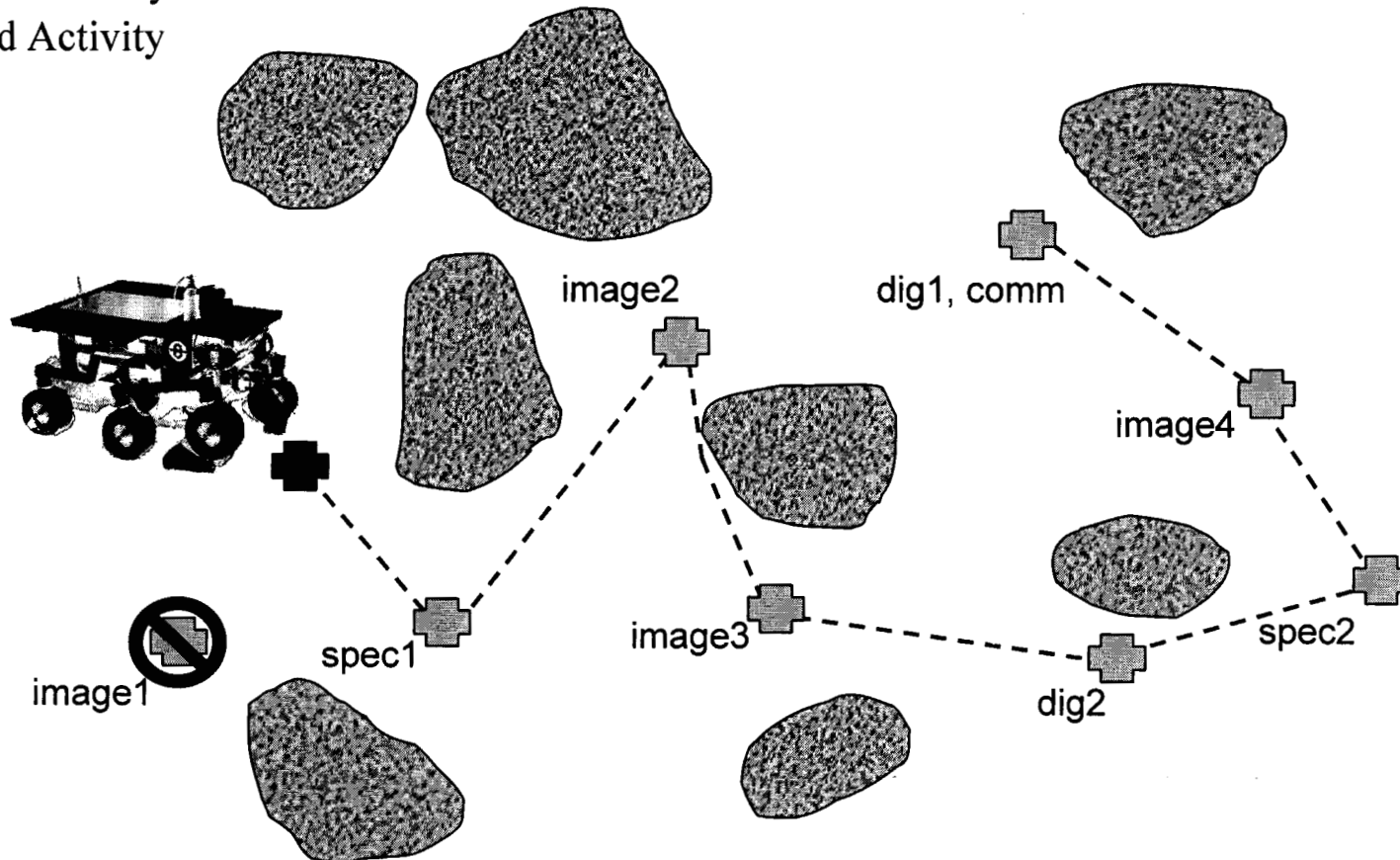
dig1

image2

image4

spec2

image3

image1

spec1

dig2
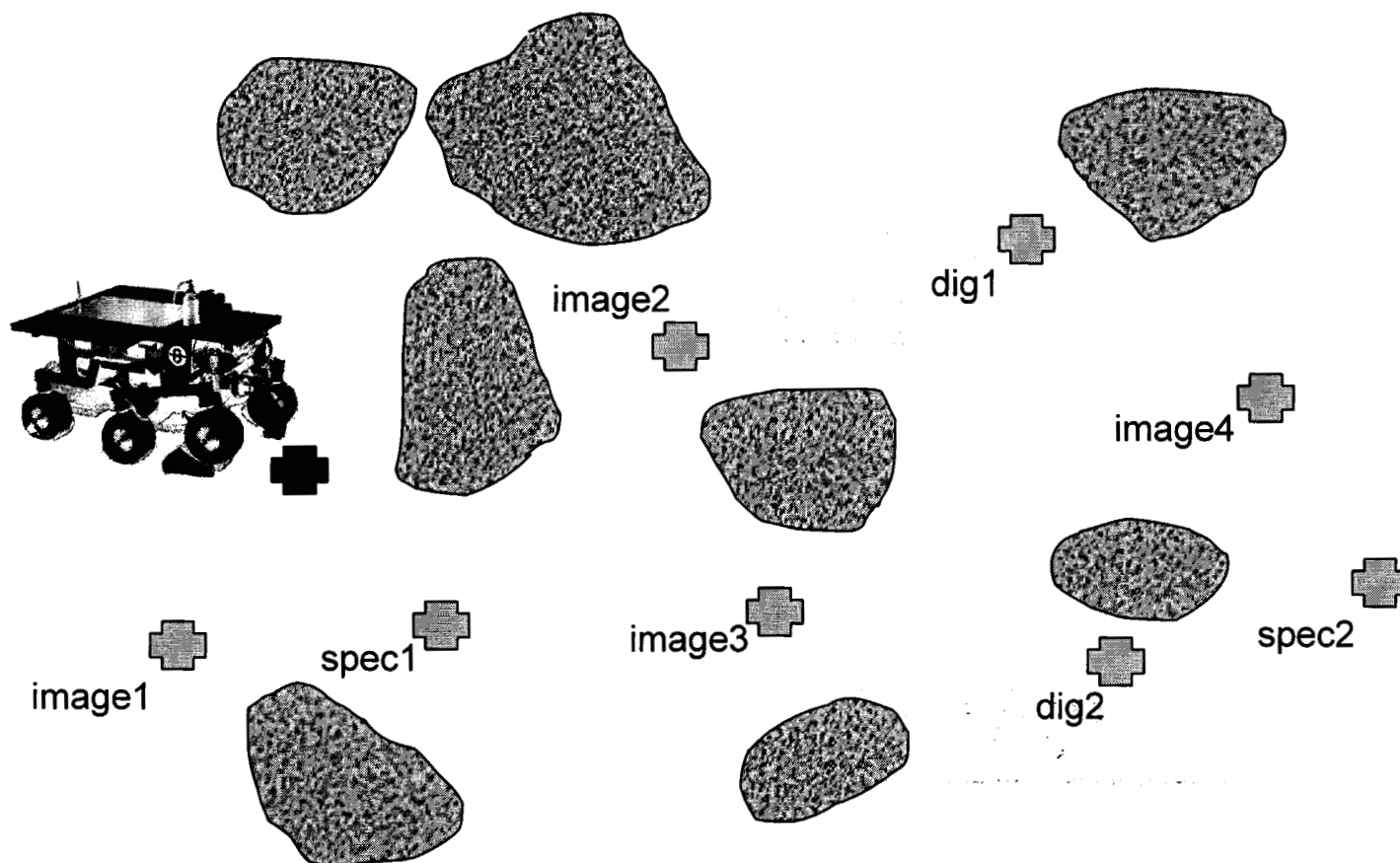
Also, end of day communication activity must be scheduled

Initial Plan

Known Obstacle
Planned Path
Planned Activity
Deleted Activity

image2

dig1, comm

image4

image3

spec1

spec2

image1

dig2

Executed Plan

Known Obstacle
Encountered Obstacle
— Planned Path
— Executed Path
—· Deleted Path
Planned Activity
Deleted Activity

3. Goal discarded due
to energy conflict

dig1

image2, comm

image4

spec2

image3

dig2

image1

spec1

2. Goal discarded due
to memory conflict

1. Targets reordered
due to obstructed path
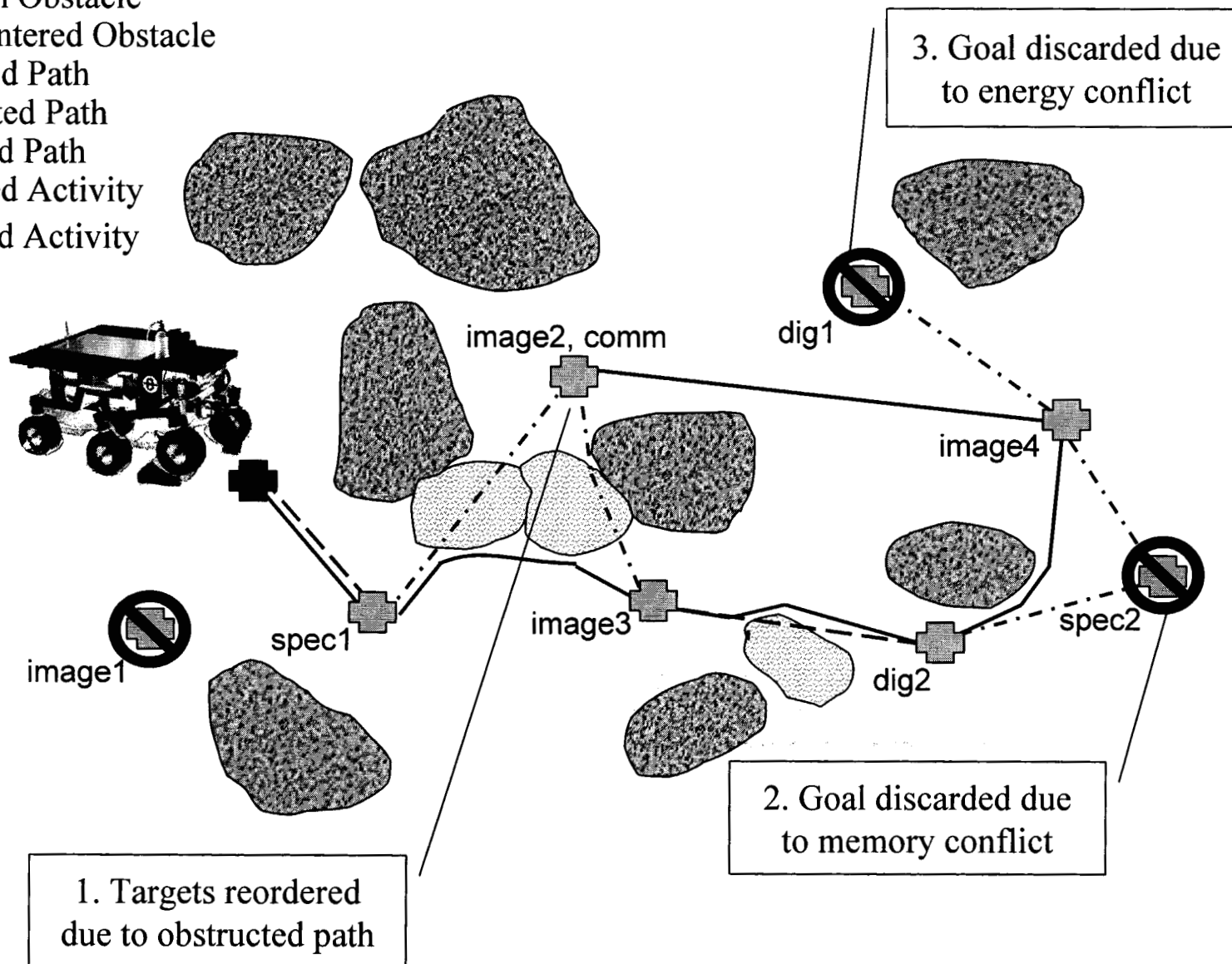
Rocky 8 Demonstration
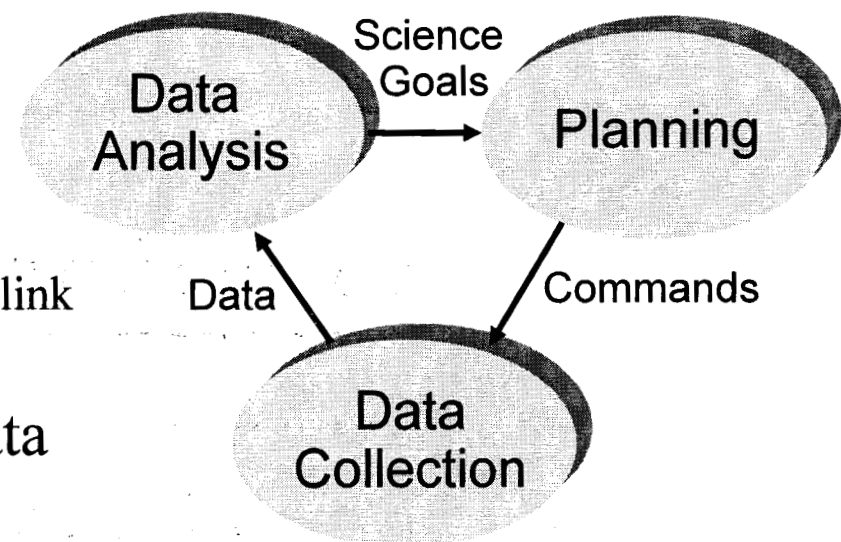
Rocky 8 demonstration in
JPL Mars Yard

Other Applicable Work

OASIS Traverse Science

- OASIS: *Onboard Autonomous Science Investigation System*
- System directed at identifying and collecting new science data during rover traverse– "opportunistic science"
- Dynamically identify new science targets by analyzing already collected data (e.g., images, spec, GPR)
- Modify rover plan using planning techniques
  - Contact earth
  - Take additional measurements
  - Alter path and take close contact measurement
- Other features
  - Intelligently prioritize data for downlink
  - Summarize data
- Currently focused on image data

Data Analysis → Science Goals → Planning
Planning → Commands → Data Collection
Data Collection → Data → Data Analysis

OASIS Technology

- **Feature Extraction**
  - Rock/Object identification
  - Feature Extraction
    - (e.g., shape, size, albedo, texture)
- **Data Analysis and Prioritization**
  - Key target signature
  - Novelty identification
  - Representative Sampling
- **Planning and Scheduling**
  - Rover plan modification
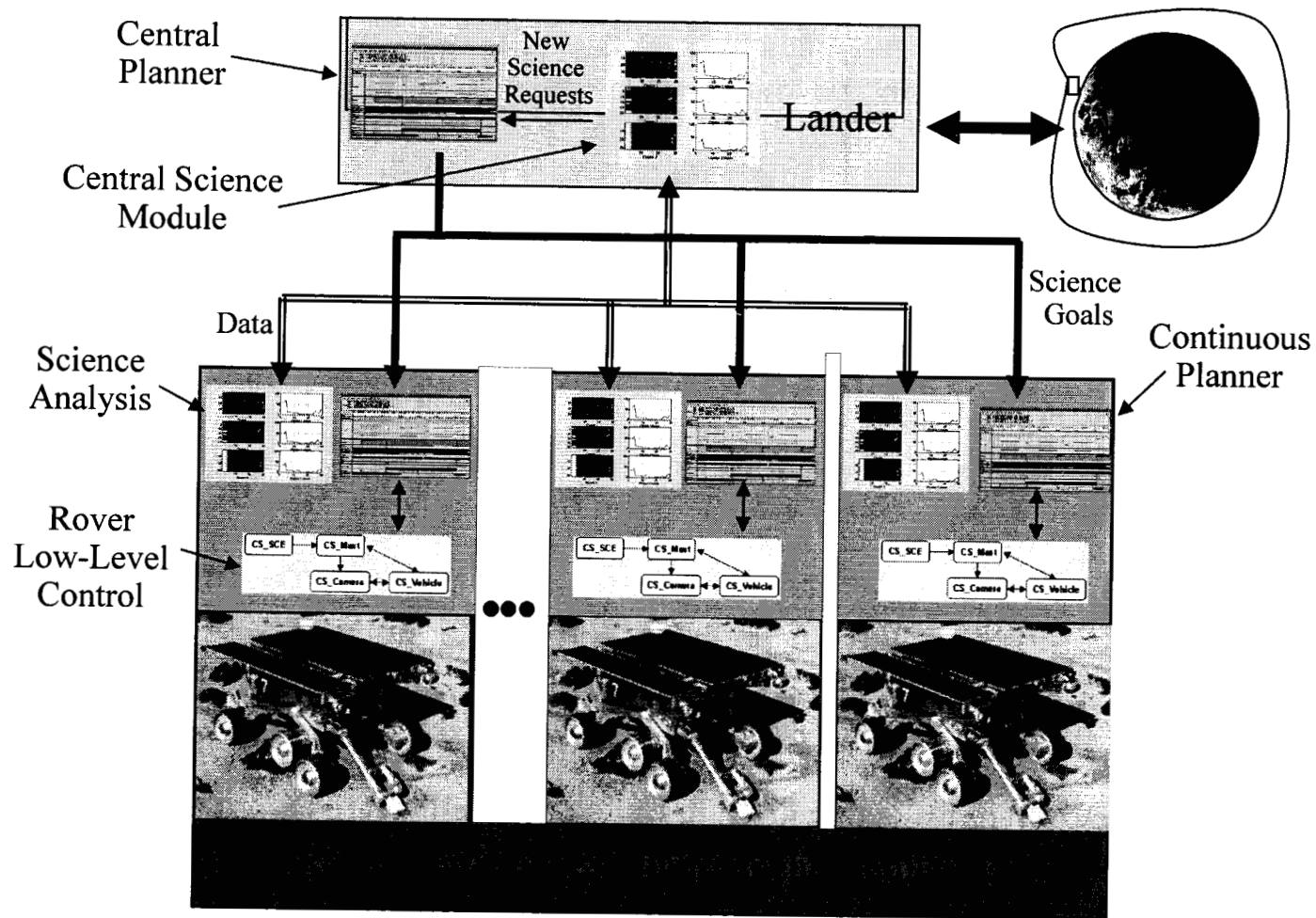 - Resource/state analysis
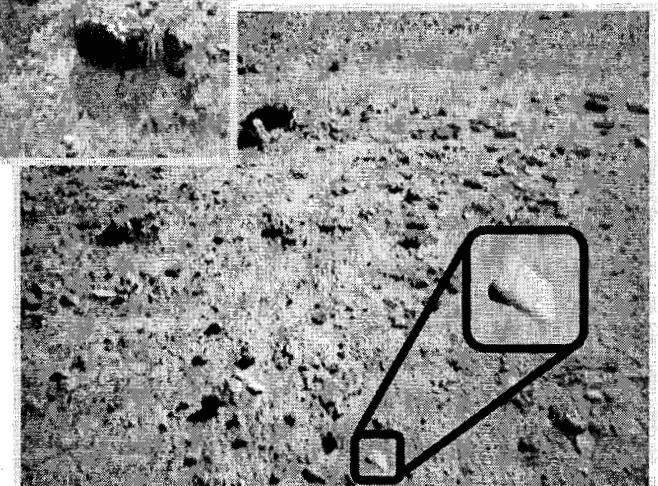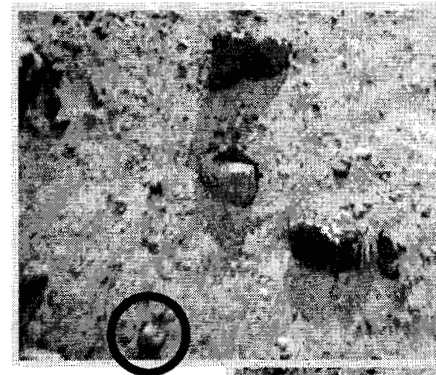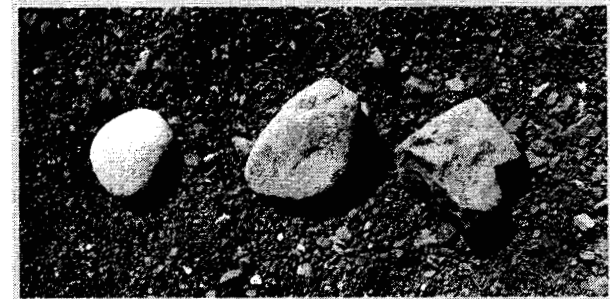
MISUS Multi-Rover Coordination

- Integrates planning and data analysis techniques to provide closed-loop science collection
- Intelligently coordinates multiple rovers in performing science operations at both command level and science level
- Data Analysis
  - Uses clustering techniques to model distribution of rock types in surrounding terrain
  - Each rover computes local model and a summary is used to create global model
  - Global model is used to determine new science targets
- Planning:
  - Central planner distributes goals among rovers
  - Each rover has onboard planner which creates detailed, executable plan for achieving assigned goals
 - Goals can be re-allocated among rovers

Central Planner

Central Science Module

New Science Requests

Lander

Data

Science Goals

Science Analysis

Rover Low-Level Control

Continuous Planner

CS_SCE → CS_Mast → CS_Camera ↔ CS_Vehicle

T. Estlin, 2/2004

MISUS Example

- Sample Scenario:
  - Determine rock distribution in surrounding area
  - Tested w/ simulator that models geological environments
- Three rovers w/ camera, spectrometer, solar panel, battery
- Science goals
  - Take images or spectral readings
  - Goals can be prioritized
- Output: model of terrain rock distribution
  - Identifies rock mineral classification and possible deposit formation
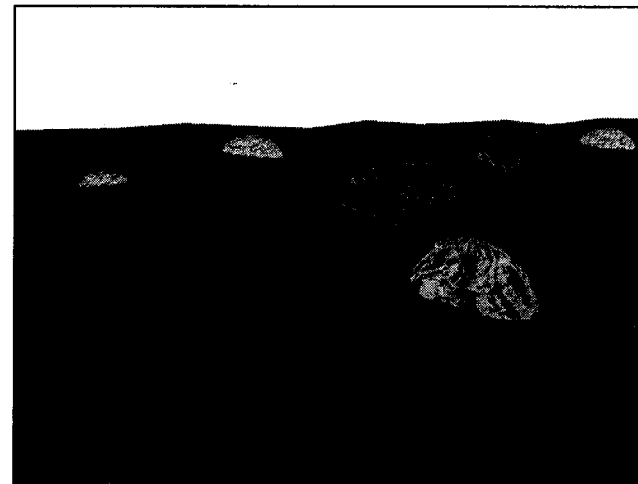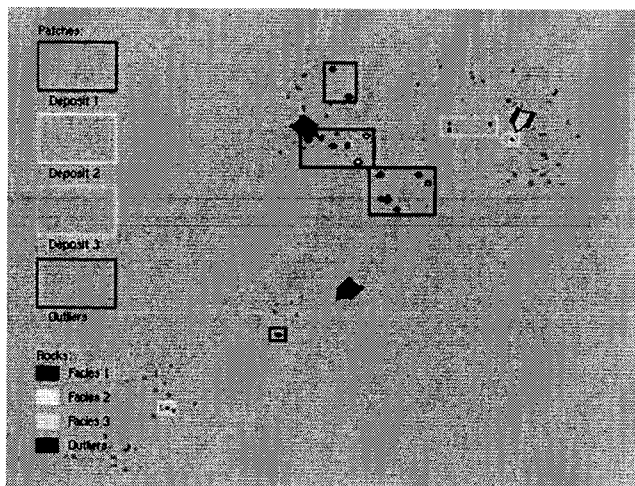
Other CASPER Deployments

- Scheduled for flight (in 2004):
  - Autonomous Sciencecraft Experiment (New Millenium Program)
    - Onboard Earth Orbiting 1 Satellitle (EO1)
    - System utilizes an integration of planning and data analysis
    - Automatically identifies and captures events of high interest
    - Also being extended to a sensor web application which uses multiple satellites
  - 3 Corner Sat (Univ of Colorado)
    - Multiple payloads onboard Air Force Satellite
    - Demonstrates stereoscopic imaging, virtual formation communications
- Mission planning tool for Antarctica Mapping Mission (MAMM) 2000
- Also applied to:
  - Ground communications station control
  - Distributed agent coordination (spacecraft and rover)